INTERNATIONAL ENERGY AGENCY
AGENCE INTERNATIONALE DE L'ENERGIE

CARBON DIOXIDE CAPTURE AND STORAGE ISSUES – ACCOUNTING AND BASELINES UNDER THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC)

IEA INFORMATION PAPER

SUSANNE HAEFELI, MARTINA BOSI, AND CÉDRIC PHILIBERT

PARIS, MAY 2004

ACKNOWLEDGEMENTS

This Information Paper was prepared by Susanne Haefeli, Martina Bosi and Cédric Philibert. The authors would like to express their gratitude to the various experts who reviewed drafts of this paper and provided comments and information. Special thanks go to Stefan Bachu, Mondher BenHassine, William Blyth, William Bonsu, John Caine, John Cameron, Melissa Chan, Peter J. Cook, Heleen de Coninck, Ralf Dickel, Jane Ellis, Sarah Forbes, Peter Fraser, Paul Freund, Tom Frost, John Gale, Dolf Gielen, Mike Haines, Wolfgang Heidung, Susan Hovorka, Jed Jones, Michael Lazarus, Arthur Lee, Mike MacMahon, Mike Moore, Kenneth Morgenstern, Jonathan Pershing, Jacek Podkanski, Ian Potter, John Shinn, Ray Rivers, Bill Senior, Tore Torp and Bill Townsend. Editing and formatting assistance from Jenny Gell and Maggy Madden was also greatly appreciated.

Questions and comments should be sent to:

Martina Bosi
Energy and Environment Division
9, rue de la Fédération
75015 Paris
France
E-mail : martina.bosi@iea.org
Fax: (33 1) 40 57 67 39

Cédric Philibert
Energy and Environment Division
9, rue de la Fédération
75015 Paris
France
E-mail : cedric.philibert@iea.org
Fax: (33 1) 40 57 67 39

IEA information papers can be downloaded from
http://www.iea.org/Textbase/subjectqueries/index.asp

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF BOXES

EXECUTIVE SUMMARY

1. This paper discusses key greenhouse gas accounting issues to be addressed before carbon dioxide (CO_2) capture and storage (CCS) activities can be included in the portfolio of climate change mitigation activities. Guidance and policies on baselines and the accounting of emission reductions will be critical to ensure that CCS projects can benefit from CO_2 markets and are recognised under various mitigation schemes.

2. Carbon dioxide capture and storage offers important possibilities for making further use of fossil fuels more compatible with climate change mitigation policies. The largest volumes of CO_2 could be captured from large point sources such as from power generation, which alone accounts for about 40 per cent of total anthropogenic CO_2 emissions. The development of capture technologies in the power generation sector could be particularly important in view of the projected increase in demand for electricity in fast developing countries with enormous coal reserves (IEA 2002a). Although, this prospect is promising, more research is needed to overcome several hurdles such as important costs of capture technology and the match of large capture sources with adequate geological storage sites.

3. CO_2 capture and storage technologies have the potential to become an important climate change mitigation option. Indeed, estimates for CO_2 global geological storage potential range from 1,000 to over 10,000 $GtCO_2$ in depleted oil and gas reservoirs, saline aquifers and unminable coal seams. This represents more than 26 to over 260 times the amount of projected energy-related CO_2 emissions in 2030. However, several issues would need to be resolved. For example, more research is needed to determine the integrity of geological storage to respond to concerns over risks of escaped CO_2 into the atmosphere. The economics will also need to be significantly improved for CCS to become a more feasible CO_2 mitigation option, with both the CCS costs and the market price for CO_2 being critical factors. Appropriate policy, accounting and baselines will also need to be developed to provide CCS with the necessary incentives and recognition. It is indeed important that CCS activities be properly accounted for in greenhouse gas inventories such as under the United Nations Framework Convention on Climate Change (UNFCCC) and emission reduction schemes such as the European greenhouse gas emissions trading scheme (due to start in 2005). In order to do so, the paper discusses issues that would need to be considered and require changes to current accounting approaches, as well as project baseline-related issues:

- It is argued that methodologies should take into account the whole processing chain from capture to long-term storage of the CO_2. This would guarantee the long-term monitoring of the storage site which is a necessary requirement. Special cases where transportation of the CO_2 imply a change in property of the CO_2, be it on a national or a private entity level, need to be considered. Cross-border transfer of CO_2 would have to deal with different accounting requirements if both countries differ with respect to their status under the Convention, the Kyoto Protocol or any such agreement. Bilateral agreements might also address this issue. Any escaped CO_2 from geological storage into the atmosphere should be reported in national inventories, for instance, under the category "fugitive emissions from fuels" or under a new category on stored CO_2;

- Under the UNFCCC, CCS could either be accounted for as a sink enhancement or a source reduction. The first possibility may be simpler, but would imply the creation of additional categories in countries' national greenhouse gas inventories. The possibility of considering CCS as source reductions can be made by countries themselves documenting a change in the emission factors they are using in their inventories (to take into account captured and stored otherwise emitted CO_2 emissions). But this may be more complex and less transparent. In addition, this paper suggests that fugitive emissions associated with transport and processing are best taken into account by reporting the actually injected CO_2 measured at the injection point, rather than by developing various fugitive emission factors all along the CCS processing chain;

- Little guidance has been provided so far regarding the modalities to calculate and account for CCS project-related CO_2 reductions under the various project-based schemes in place or in development. The three baseline approaches defined in the Marrakech Accords for the Kyoto Protocol's Clean Development Mechanism seem to provide a good basis for the accounting for CCS activities. However, additional guidance is needed on the accounting for the energy penalty which can be very important for projects involving CCS at power generation plants. A plant's historical emissions in case of a retrofit with capture equipment could constitute a baseline but the possible additional emissions arising from the replacement of the lost power of the plant also need to be taken into account. In such cases, baseline methodologies developed to estimate grid-based emission factors (e.g. "combined margin") would be applicable for the calculation of emissions associated with the energy penalty. Another baseline methodology possibility would be to consider the emissions that would have happened from a similar plant without capture equipment, but with an output equivalent to that of the plant with capture equipment. This latter possibility is likely to be the most appropriate for greenfield equipments. If CO_2 emissions can easily be monitored, then emission reductions associated with the CO_2 capture from conventional power plants or other combustion installations – and thus the basis for the issuance of emission credits – could be calculated as the difference between the captured CO_2 and the CO_2 associated with the CCS energy penalty;

- Escaped CO_2 from geological storage into the atmosphere would require a different treatment under project-based mechanisms especially if host countries are not subject to quantified emission objectives. All efforts should be taken to avoid such emissions escaping from the onset, but it would be important to recognise and take into account risks – even public perceptions of risks – of escaped CO_2 associated with CCS activities. Analysis of the possible use of discount factors to tackle this issue is underway and may provide practical means of including the likely risks of escaped CO_2 into account in a satisfactory manner.

INTRODUCTION

4. Energy use and consumption are projected to increase significantly over the coming decades. World primary energy demand is expected to steadily increase by an average of 1.7 per cent per year until 2030. To meet this demand, projections indicate an increase in virtually all forms of energy supply. Average annual growth is expected to be 1.4 per cent for coal, 1.6 per cent for oil and 2.4 per cent for gas. This would result in increased emissions of greenhouse gases: +70 per cent between 2000 and 2030, amounting to 38 billion tonnes of energy-related CO_2 emissions emitted worldwide in 2030 (IEA, 2002a).

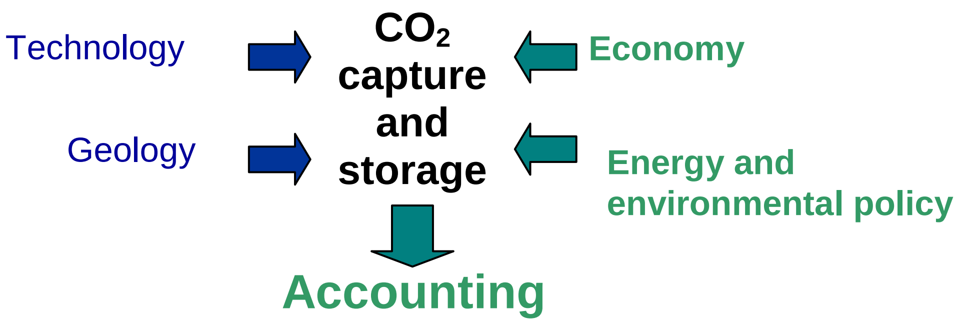
5. The challenge of limiting GHG emissions and meeting the ultimate objective of the UNFCCC (i.e. stabilising their atmospheric concentrations at a level that would prevent dangerous anthropogenic interference with the climate system) appears formidable, as stabilisation of CO_2 concentrations at any level may eventually require near-elimination of CO_2 emissions (IEA 2002b). Greater efficiency in the converting and using energy, fuel switching towards less carbon-emitting fossil fuels, phasing in more non-carbon emitting energy sources, are all means to limit energy-related CO_2 emissions. Carbon dioxide capture and storage technologies (CCS) could also be part of the solution (McKee, 2002). In fact, CCS is believed to bear great potential to reduce anthropogenic greenhouse gas emissions over the coming decades. The estimates for CO_2 global geological storage potential range from 1,000 to over 10,000 $GtCO_2$ in depleted oil and gas reservoirs, saline aquifers and unminable coal seams. As a comparison, 2001 global CO_2 emissions from fuel combustion amounted to about 24 $GtCO_2$ (IEA 2003b) and are projected to reach 38 $GtCO_2$ in 2030 (IEA 2002a).

6. CCS research and development activities, as well as screening of geological possibilities and working to match CO_2 sources with reservoirs are underway in many regions. Most activities and initial experiences are concentrated in Japan, North America, Australia and Europe due to political pressures and commitments to reduce CO_2.

7. Figure 1 shows the five research areas affecting the development of CCS projects: (i) technology; (ii) geology; (iii) economics; (iv) energy and environmental policy; and (v) emission reduction calculations and accounting. CCS has become an important research area in many governments and organisations, including under the auspices of the International Energy Agency (IEA). The IEA Implementing Agreement on GHG Research and Development focuses on various R&D activities in technology and geology in collaboration with various governments and private entities (see http://www.ieagreen.org.uk). The IEA work includes economic modelling of capture options, their respective costs as well as their comparison to other CO_2 emission reduction options (Gielen 2003a and b). It also examined policy issues linked to CCS, such as public acceptance, legal health, safety and environmental issues, and instruments to bring costs down (IEA, 2003a).

8. The purpose of this paper is to focus on CO_2 accounting and baseline-related issues and to contribute to the development of policy and guidance for CCS projects. CCS could be undertaken as part of national or international schemes, such as the Kyoto Protocol's project-based mechanisms (i.e. Joint Implementation and the Clean Development Mechanism). Guidance and policies on baselines and the accounting of emission reductions are critical to ensure that CCS projects can benefit from CO_2 markets and are recognised under various GHG mitigation schemes.

Figure 1: Factors influencing CCS and their Success in Reducing Anthropogenic CO_2 Emissions



9. The major issues that need to be resolved for the development of CCS projects are briefly described below:

- **Technology:** According to experts, various solutions to capture, transport and store CO_2 already exist (they are shortly described in the next section of this paper). The main challenges are to decrease the costs of capture and to put in place the distribution infrastructure between the capture and the storage sites, as well as to bring down the energy costs incurred in the process of capturing CO_2 emissions;

- **Geology:** Long-term storage is possible in depleted oil and gas fields, unminable coal seams, and saline aquifers. The latter have the largest potential storage capacity and findings from research to date suggest that they provide stable reservoirs. However further research is needed to determine with greater certainty the extent of the storage potential[1] and the adequacy of their storage integrity. Proving that storage will last over the long term and adequately responding to concerns over risks of escaped CO_2 into the atmosphere are key challenges. It is also necessary to match anthropogenic emission sources with safe geological storage formations, which requires investment in the necessary transportation infrastructure;

- **Economics:** Current cost estimates range from 15 to 87 US\$/tCO_2 for capturing the CO_2 with an effect of 0.6-3.3 US cent per kWh and 5 to 20 US\$/tCO_2 for transportation (not including the capital costs of building new pipelines[2]) and injection (Davison, 2002). These costs are expected to decrease in 10-20 years time so that CCS might prove to be a more feasible CO_2 mitigation option. One key issue is how a market price for CO_2 could affect CCS activities, as the economic feasibility of CCS activities will often depend on a sufficient monetary value being given to CO_2 emissions;

- **Policy:** Health, safety and environmental issues must be considered, and may condition public acceptance. Existing legislation or regulations, as well as international agreements

[1] The questions of storage potential and requirements resulting from health, safety and environmental regulations are not unrelated. Strict regulations would likely diminish the storage potential compared to less strict regulations.

[2] Some CCS projects might require the building of new pipelines, which would increase the total cost of CCS.

and regional conventions (e.g. OSPAR) may apply at various stages, but more specific CCS legislation may be required (IEA 2003a);

- **Accounting and baselines:** CCS technologies can provide near-elimination of CO_2 emissions when fossil fuels are combusted, and even negative emissions when biomass fuels are combusted[3]. However, current accounting methods used by the Parties to the UNFCCC are based on the assumption that fuel combustion automatically leads to CO_2 emissions. Thus, modification of existing methodologies, or definition of additional methodologies, must be made to take into account the impact of CCS technologies on CO_2. Furthermore, in order for CCS project activities to be included in project-based mechanisms, it is necessary to consider methodologies to develop emission baselines to calculate emission reductions generated by these projects.

10. The development of rigorous baselines is necessary to guarantee the integrity of a reduced tonne of CO_2. Yet, baselines are hypothetical scenarios representing "what would have happened otherwise"[4]. As outlined in previous IEA/OECD baselines work (e.g. OECD/IEA, 2000), while baselines are impossible to prove (as "what would have happened" does not happen), ideal baselines should be: (i) credible from an environment perspective; (ii) transparent; (iii) simple and practical leading to low transaction costs; as well as (iv) limit the crediting uncertainty for project developers and investors. Accounting rules should build on the principles of financial accounting, i.e. relevance, completeness, consistency, transparency and accuracy while not being too cumbersome. In order to ensure that any CCS project activities to reduce CO_2 emissions are treated on a level playing field with other mitigation options, it is necessary to clarify various concepts and issues specific to CCS projects and to prepare reporting guidelines as early as possible.

11. This paper acknowledges the ongoing work of the Intergovernmental Panel on Climate Change (IPCC) on a special report on CCS projects (forthcoming, 2005), part of which will address related accounting issues. The IPCC is also in the process of revising the guidelines for national greenhouse gas inventories, forthcoming in 2006. In the meantime, it is hoped that this paper can contribute to that work and provide a basis for fruitful discussions on how best to integrate CCS in the overall climate mitigation effort.

12. This paper seeks to contribute to the assessment of policy issues linked to CCS and focuses on the geological sequestration of CO_2. Oceanic injection and biological sequestration are very different from CO_2 injection into geological storage sites and they are not treated in this paper[5].

---

[3] Negative emissions (and thus positive sequestration, such as for forestry sinks projects) would be possible due to the IPCC Guidelines for National Greenhouse Gas Inventories recommendations that for all burning of biomass fuels, the net CO_2 emissions be treated as zero in the energy sector (assuming that biomass fuels are sustainably produced. For more discussion on biomass energy with CO_2 capture, please refer to Möllersten et al (2003) or Obersteiner et al. (2001), for example.

[4] Such is the role of baselines in the case of the Kyoto Protocol's Joint Implementation and Clean Development Mechanism. In domestic project-based schemes, baselines could be developed to represent, for example, a given performance standard, or even "what *should* happen otherwise" (to take into account national GHG targets).

[5] For more information on accounting issues surrounding biological sinks, see www.unfccc.int and for research on oceanic sinks, see http://www.ieagreen.org.uk/ocean.htm

13. Section 1 outlines the possibilities of capturing, transporting and storing CO_2 in order to crystallize relevant definitions of CCS activities important for greenhouse gas accounting purposes. Section 2 looks at some important issues when accounting for CCS activities under the UNFCCC and Section 3 discusses the possible methodologies of establishing baselines accounting for any escaped[6] CO_2 under project-based mechanisms.

I. OVERVIEW OF THE PROCESS FROM CO_2 CAPTURE TO STORAGE (CCS)

14. CO_2 is already captured from some industrial processes such as hydrogen production at little or no additional cost, and is already being separated in others – such as natural gas sweetening[7]. Currently, these CO_2 emissions, once separated, are generally vented, as there are little – if any – economic incentives to do otherwise. Only two projects in Norway and the United States currently capture the CO_2 separated from natural gas and inject it underground (see Boxes 1 and 2). Small quantities of CO_2 nonetheless find a valuable use in sectors such as the food industry. The petroleum sector has also found some use for CO_2. There, CO_2 – mostly coming from natural underground reservoirs, as it is more readily available than captured CO_2 from flue gases – is transported and injected in enhanced oil recovery operations (EOR), especially in the United States and Canada.

15. The largest volumes of CO_2 could be captured from various large point sources i.e. fossil fuel combustion processes such as for power generation, cement and metal production. This is currently not being done due to the high costs of the capture technology, the lack of CO_2-limiting legislation and the lack of demand for captured CO_2. However, current cost estimates are expected to come down so that CCS might deploy its large-scale potential as a CO_2 mitigation option in carbon-constrained economies (Gielen, 2003a and Herzog, 2000). In the meantime, current and forecast prices not exceeding 15 € per tonne of CO_2 would only marginally affect decisions on whether or not to embark on CCS technologies. However, in case of EOR operations (or enhanced coal bed methane), the resulting additional fuel recovery provides significant revenues. The US oil companies involved in EOR operations are now paying 7 to 8 US$/t CO_2, which gives an indication of the net revenues.

16. Capture processes can be divided in three groups (Thambimuthu, 2002):

(1) **Post combustion/Gas scrubbing routes**, in which the CO_2 is scrubbed from the gas exiting the combustion or production process. These are the most commonly used technologies today and, for example, they can capture up to 99 per cent of the processed/flue gas exiting a boiler or a gas sweetening unit;

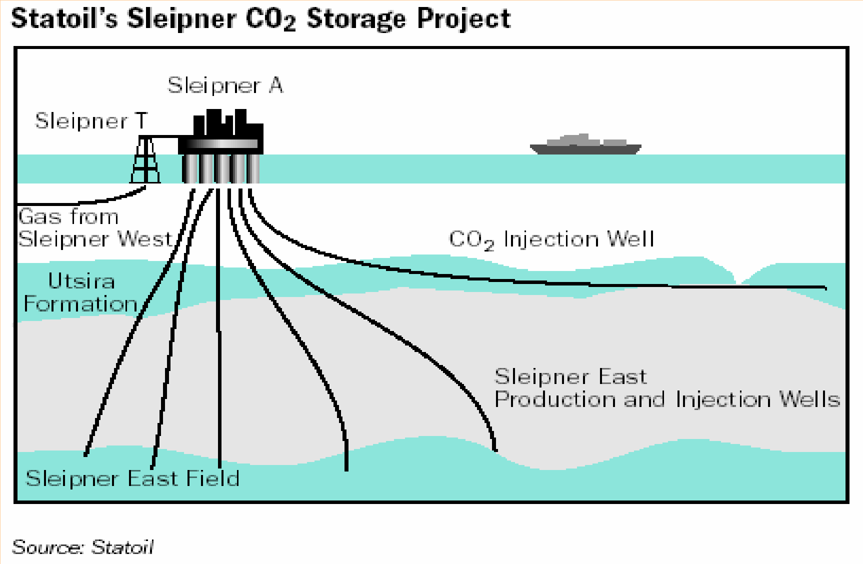
(2) **Pre-combustion/Syngas approach**, in which a synthetic hydrogen and CO_2 rich gas is produced from the fuel. This approach is used in integrated gasification combined cycle plants (IGCC). It is a clean coal technology under development with few already existing plants in Europe and the US, but with promising prospects as a large-scale technology;

3) **"Oxyfuel"** routes, in which the combustion process is fired with oxygen rather than air to create a flue gas primarily comprising CO_2. This approach is still in a R&D phase.

[6] Escaped CO_2 refers, in the context of this paper, to emissions that leak directly from the storage site into the atmosphere.

[7] i.e. removing excess CO_2 from natural gas.

Box 1: The Sleipner CO_2 Injection Project



About one million tonnes of CO_2 per year (or nearly 3 per cent of the Norwegian CO_2 emissions in 1990) have been injected into the Utsira saline aquifer 1,000 metres below the sea bed since October 1996. The CO_2 capture based on a standard amine absorption process, takes place directly at the Sleipner T (Treatment) platform where it is also compressed. The CO_2 injection and storage operation resulted in an 80 million additional investment compared to an alternative scenario where the gas is emitted to the atmosphere, and has paid back in about one and a half years solely on the basis of the carbon tax savings (about 50 € per tonne of off-shore vented CO_2). The captured CO_2 is not reported under the Energy sub-category "Fugitive emissions from venting and flaring" of Norway's GHG inventory as the injected CO_2 is assumed to be permanently removed from the atmosphere. When the injection has to stop for maintenance etc. the CO_2 vented to the atmosphere is included in the national inventory (national inventory report Norway, 2003 and IEA Greenhouse Gas R&D Programme at www.ieagreen.org.uk/sacshome.htm)

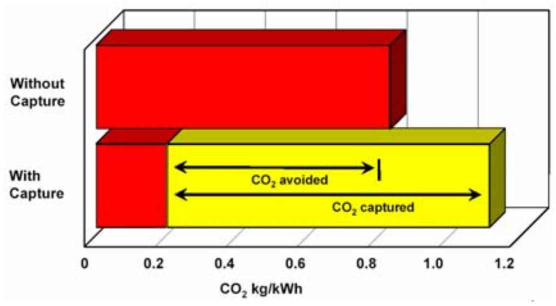
17. All three processes consume a significant amount of energy, and thus entail costs. This is referred to as the "energy penalty" of the capture process. The energy penalty typically ranges between 15 to 40 per cent of the energy output in the case of CO_2 capture at a coal-fired power plant; it is illustrated by an example in Figure 2.

18. If the coal-fired power plant emits, for instance, 0.8 tCO_2/kWh, the CO_2 released due to the additional power generation needed to capture the CO_2 is partly captured together with the CO_2 from the primary power generation process. Total captured emissions are thus greater than those actually avoided, as the additional power generation would not have occurred in the absence of the capture process.

19. Material loss can be important in the case of flue gas scrubbing routes. As an example, amine – a chemical absorbent used to scrub the CO_2 off the gas – reacts irreversibly with SO_2, and SO_3, producing stable salts that are not reclaimable. These salts are highly corrosive to plant components and cause loss of amine. Production of amine production is energy intensive and the emissions due to

amine losses should be taken into account. Fugitive CO_2 emissions can arise from imperfect capture process and from devices such as compressor valves.

Figure 2: The Energy Penalty in the CO_2 Capture Process



Source: IEA GHG R&D, 2003

20. After capture, CO_2 can be transported under high-pressure in pipelines to a long-term storage site. There is about 3,000 km of large land-based CO_2 pipelines in existence throughout the world, of which 2,400 km are in the United States alone where CO_2 has been transported since the early 1980s (about 44 Mt CO_2 per year is transported in the U.S.). As a comparison, about 800,000 kilometres of pipelines carry natural gas in the US (DTI, 2002). In Europe, a smaller infrastructure of CO_2 pipelines is operated between chemical plants.

21. CO_2 is transported in ships in North Western Europe with typical CO_2 transport capacity currently around 300,000 tonnes annually. Only small quantities of CO_2 are transported by road. The design of a CO_2 tank is similar to existing LPG carriers, the pressure being higher and the temperature being lower for CO_2 transport.

22. In order to be transported, the CO_2 needs some pre-treatment such as desulphurization, dehydration and compression. The transportation itself also uses some energy – though associated emissions are likely to be very small in comparison with the amounts stored.

Box 2: Petro Source's Capture of vent-stack CO_2 in combination with EOR

Since 1998, Petro Source delivered about 840,000 tCO_2 annually to three crude oil production operators in West Texas for EOR. The source of CO_2 supplied by Petro Source was waste CO_2 gas from four natural gas treating plants, which previously vented these streams to the atmosphere.

To calculate avoided CO_2 emissions, the baseline has been defined as the CO_2 which would have been released to the atmosphere in the absence of Petro Source's operations. As the gas vented from the gas plants is difficult to measure, the net emission reduction calculation is based on the metered volume of sales gas minus the emissions due to Petro Source's operations called "creation period leakages". This includes combustion emissions associated with compression of CO_2, indirect emissions from electricity used for preparation for transportation (not including energy used for de-hydration) and during transportation, fugitive emissions from equipment components and emissions associated with the recycle of CO_2 from the EOR. Possible physical leakage from the reservoir plans on how to decommission the field after the project's end and long-term monitoring is not addressed. Uncertainty on the permanence of the stored emissions (i.e. if future technological advances or fuel prices make it economical to extract additional hydrocarbons, and hence previously stored CO_2 will resurface) is acknowledged but not included in the calculations.

The project is registered with the Canadian Voluntary GHG Reduction Registry. Further information can be found at http://www.vcr-mvr.ca/registry/out/P0275-PS-ERC-PDF.pdf .

23. Fugitive emissions due to transport and distribution losses occur at compressor and pump stations and at the point of loading and unloading of the CO2. Significant and measurable CO2 breakthrough at pipelines is rare and comparable in frequency per kilometre of length to natural gas leaks (IEA 2003a). The impact of a CO2 leak is likely to be much less hazardous than a natural gas leak, as CO2 is not flammable or explosive. As CO2 is denser than air, hazardous build-ups could only occur in situations where the air is stagnant, for instance due to topography or weather conditions.

24. Fugitive emissions can occur during the above-mentioned processes and CO_2 emissions can leak in the event of seepage from the storage site, as well as from running of long-term monitoring processes ranging from intrusive instrumentation to remote technologies, such as seismic surveys and imaging.

25. CO_2 can be stored in depleted oil and gas fields, unminable coal fields and saline aquifers. These reservoirs are abundantly available all over the world and the oil and gas fields are especially well documented. These reservoirs could store CO_2 for thousands of years but certain elements are relevant to their integrity:

- **Natural setting:** Current research assesses and classifies storage sites according to criteria such as tectonic activity, geothermal regime and surrounding rock characteristics. Storage site integrity varies from very safe with no foreseen seepage to rather unsafe sites with great risk of seepage. Considerable legislation regarding the natural setting is already in place in most IEA Member countries for seasonal natural gas storage, permanent acid gas and waste injection, but it is not clear whether CO_2 would fall under one of these existing categories;

- **Integrity of the caprock:** The history of human usage of potential reservoirs might be important to consider, especially in the case of depleted oil and gas fields where numerous wells may have been used and constitute many potential leakage pathways;

- **Quality of well and sealing package:** CO_2 can migrate along the wells and at the sealing package depending on their quality and age. The stringency of current sealing methods for abandoned oil and gas sites depends on the distance to human habitat and the use of the storage site, e.g. acid gas storage site seals need to be very safe;

- **Possibility of unforeseeable events:** In a worst case scenario, one might think of CO_2 storage sites fractured by an earthquake. Contrary to the above seepage possibilities, the event of an earthquake could bear the risk of significant and rapid escape of CO_2 into the atmosphere. If the surrounding topography trapped the CO_2 which is heavier than air, a dense cloud might form and might suffocate humans and animals in its proximity.

26. The degree of site integrity necessary to qualify for long-term CO_2 storage, and the precautionary measures to be taken before and during storage are ultimately political decisions that will need to be taken.

27. It is difficult to predict all risks related to injecting very large volumes over long time frames. In addition, given the limited CCS experience, there are little data available to obtain a quantitative estimate of actual risks – if any – of CO_2 escaping from geological sites. However, useful insights and assumptions can be derived from the existing literature on site integrity.

28. It would seem reasonable to assume that science is sufficiently advanced to identify storage sites with high environmental integrity and that this integrity could be assured with political measures over time and to a degree that allows the consideration of geological CO_2 storage sites as part of climate change mitigation efforts. However, possible concerns by environmental NGOs and local stakeholders over risks of escaped CO_2 into the atmosphere and other environmental risks, especially over the long-term, should be addressed. (IEA, 2003a).

29. Site integrity assessment needs to be undertaken before the start of CO_2 injection and is specific for every storage site. Public outreach to address local health, safety and environmental concerns or risks would also be necessary to successfully implement a CCS project (IEA, 2003a). Long-term monitoring and security requirements will likely be site-specific as well. In this context, future monitoring guidelines could mention the need for:

- Collection of relevant data regarding site integrity, potentially affected habitats and infrastructure development, location of sealed wells and underground movement of CO_2;

- A description of present and expected evolution of legal title to the land, rights of access and insurance cover;

- Clear signalling of sealed wells;

- Stakeholders' involvement and integration in decision and management processes including capacity-building and awareness raising;

- Adequate measures and risk management plans being in place in case of an unforeseeable event; and

- Using best available monitoring processes and technology.

30. The assurance of some kind of long-term site integrity seems to be imperative. Mid-term monitoring, e.g. up to 30 years, might be borne jointly by the public and private sector for a certain period of time, but long-term monitoring will probably have to be assured by the country in whose territory the CO_2 is stored. Further legislation, possibly at the international level, would be needed for CO_2 injected in geological storage sites under international waters.

31. CO_2 can be injected in almost-depleted oil fields in order to enhance oil production. In North America, about 40 $MtCO_2$ are used annually for Enhanced Oil Recovery (EOR), mostly coming from natural CO_2 reservoirs, abundantly available in these regions and transported over distances up to 800 km in pipelines (IPCC, 2002). When CO_2 ultimately breaks through at the producing well it is normally separated from the oil stream and re-circulated back into the system. One-half to one-third of CO_2 in EOR is typically not recycled, of which a significant fraction is thought to be trapped permanently.

32. Unlike oil reservoirs, CO_2 is not currently used to enhance the recovery of natural gas because it is still unproven and involves recognised risks. The economics could also be problematic given the limited gas recovery resulting from CO_2 injection and the cost of re-separating CO_2 from the recovered methane.

33. Another potential storage medium is unminable coal. CO_2 can be injected into suitable coal seams where it will be adsorbed by the coal, locking it up permanently – provided the coal is never mined. This process produces methane which is ousted by the incoming CO_2. There have been few Enhanced Coal Bed Methane (ECBM) trials in the world to date, but some estimates have been developed by different organisations. For example, based on a forecast of CBM production made by Canada's National Energy Board, it is estimated that 380 $MtCO_2$ could be stored each year by 2025 – approximately half of Canada's current GHG emissions. A similar picture emerges in Australia, China and elsewhere in the world where coal permeability is sufficient to allow CO_2-ECBM operations. According to IEA GHG R&D programme data, the potential for CO_2 storage via ECBM is estimated to amount to 100-150 Gt in total, with an estimated 40 Gt economic potential. To put this into perspective, it is interesting to compare these figures to 2001 world energy-related CO_2 emissions which amounted to 23.7 $GtCO_2$ (IEA 2003b) and projected world energy-related CO_2 emission, i.e. 38 $GtCO_2$ (IEA 2002a).

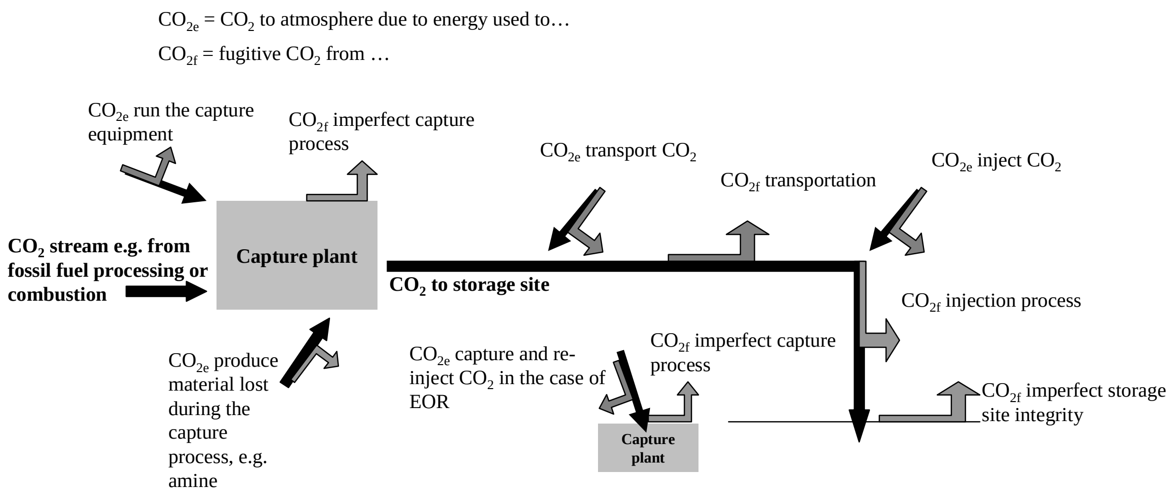
34. Are enhanced oil recovery and coal bed methane projects comparable to CO_2 storage in other geological formations? From a technical point of view, EOR projects differ from long-term storage in that a significant part of the CO_2 resurfaces with current practice, which is actually desired as CO_2 is a commodity i.e. the entity pays for it. In both EOR and CBM activities, the focus of the activity is currently not on storage site integrity. It can, therefore, be assumed that assurance of the long-term

storage of CO_2 would need resources in the form of preliminary studies and enhanced well-plugging, additional to those required in the absence of the climate change mitigating project.

35. Emissions associated with the storage process may occur from the energy used to operate the injection equipment. If CO_2 breaks through at the production well in the case of enhanced oil, gas and coal bed methane recovery, it is normally separated and re-injected, which uses additional energy.

36. Figure 3 illustrates the possible CO_2 emissions occurring from capture to storage, not taking into account other emissions such as NO_x and SO_2 occurring from energy production.

Figure 3: Possible Emissions Occurring During CCS



37. In order to ensure the integrity of GHG reductions and to properly account for the GHG impact of CCS projects, it is necessary to consider the whole processing chain from capture to storage. The importance of this requirement can be illustrated with two examples: (1) it would make little sense from a climate change mitigation point of view to acknowledge emission reductions occurring from the injection of naturally occurring CO_2 in enhanced oil recovery as the net balance of CO_2 in the atmosphere is at its best zero in the event of all CO_2 being ultimately stored; (2) equally, in many cases, it would make little sense to accredit projects involving CO_2 capture where the CO_2 would be used by the food or chemical industry since it will return to the atmosphere quite quickly (unless it could be demonstrated that CO_2 emissions from other fossil fuels are avoided by displacing them by using captured CO_2).

38. Another important emission accounting issue arises because CCS is the only climate change mitigation activity where CO_2 is physically transported and hence can change ownership be it on a national or private entity level.

39. A possible definition of CCS projects could be divided into three parts:

- **Capture of CO_2** from a source i.e. any process or activity which releases CO_2 into the atmosphere due to anthropogenic activity, such as defined in article 1 of the UNFCCC[8];

- **Compression and transport of CO_2** from a defined capture site to a defined storage site;

- **Geological storage[9] of CO_2** i.e. injection of CO_2 in underground geological formations with a high integrity. Geological storage should be distinguished from *biological sequestering* (land-use, land-use change and forestry) or *oceanic sequestering injection* of CO_2 as – although all removing CO_2 from the atmosphere, at least temporarily – they differ substantially in various aspects. Table 1 shows some of the differences.

40. Other tendencies of convergence in terminology tend to use more and more "CO_2 capture and storage" instead of "carbon capture and storage" as the latter term comprises other meanings than carbon in its oxidized form.

41. Further terminology clarifications could be helpful:

- **Leakage versus fugitive emissions:** CCS experts tend to refer to leakage when discussing storage site integrity, whereas in the case of project based mechanisms under the Kyoto Protocol, the term leakage is defined as "(…) the net change of anthropogenic emissions by sources and/or removals by sinks of greenhouse gases which occurs outside the project boundary, and that is measurable and attributable to the (…) project" (Decision 16/CP.7 Appendix B and Decision 17/CP.7, art. 51, Marrakech Accords, add. 2). "Fugitive emissions" are defined in the IPCC 1996 national GHG inventory guidelines[10] as "intentional or unintentional releases of gases from anthropogenic activities. In particular, they may arise from the production, processing, transmission, storage and use of fuels, and include emissions from combustion only where it does not support a productive activity (e.g., flaring of natural gases at oil and gas production facilities)". As the term leakage is already widely used to describe both meanings, another possibility, as is done in this study, might be to call emissions that escape to the surface from the geological formation into the atmosphere "leaked CO_2"[11] or "escaped CO_2" and use the term "indirect leakage" when referring to emissions occurring outside the project boundary as mentioned in the Marrakech Accords' provisions on JI and CDM. "Fugitive emissions" refer to CO_2 losses during transport and processing;

[8] Art. 1 of the UNFCCC defines "source" as any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere (www.unfccc.int).

[9] Current efforts to create a common language in the CCS sector tend to use the term "storage" for geological, as opposed to "sequestration" often used in the case of biological sinks. It may be noted, though, that the Kyoto Protocol uses the term "sequestration technologies" in its Article 2 a) iv.

[10] i.e. the IPCC GHG Inventory Guidelines on fugitive emissions from energy and industrial processes.

[11] These terminology suggestions might need to be revised as a result of ongoing IPCC discussion on CCS issuses.

- **Term for “storage site”:** The UNFCCC defines the terms “reservoir” as “*a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored*” (Art. 1.7, UNFCCC). Art. 4.1 (d) further defines reservoirs as including “*biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems*”. In order to distinguish different types of reservoirs it would be helpful to agree on a specific term for geological reservoirs such as “stock”, “depot” or “repository”.

42. It may be noted here that throughout this paper, “emission reduction” or “avoided emission” is used when talking about the technical aspects of CCS, e.g. fugitive CO_2 emissions. “Offset” defines the avoided emissions within the legal and accounting framework. “Credit” refers to tradable emission units with a monetary price and, in a more narrow sense, emission reductions created under a project-based accounting scheme.

Table 1

Some CO_2 Accounting Differences between CO_2 storage/sequestration Options: Land-use, Land-use Change and Forestry (LULUCF), Ocean Injection and Geological Reservoirs

Accounting issue	LULUCF	Ocean Injection	Geological Reservoir
Assessment method of CO_2 uptake	calculations and estimates, depending on various exogenous factors such as climate, plant and soil specificities	estimates based on modelling of currents	injected amount is measurable
Permanence	tens to hundreds of years, depending on the life of the plant or the soil activity	possible for more than 1,000 years (e.g. the injection of CO_2 into the down welling region of the Greenland sea), depending on the currents	Thousands of years, depending on the natural setting and the quality of the sealing package
Unforeseeable events	e.g. fire, inundation	changes in oceanic currents, earthquakes, tsunami, etc.	e.g. earthquake,
Additionality	may be done for other reasons than climate change e.g. plantations	sequestration is done for the sake of climate change mitigation only	long-term storage is usually done for the sake of climate change mitigation only except in case of EOR operations
Escaped CO_2 into the atmosphere	difficult to monitor	most difficult to monitor	difficult to monitor
Environmental impact	use of monocultures and alien plants which impedes on the territory’s biodiversity	possibly large but not yet entirely understood.	CO_2 escaping from storage could affect aquifers, surface waters and land surface

II. ACCOUNTING FOR EMISSIONS UNDER THE UNFCCC

43. Under the UNFCCC, "(…) all Parties, taking into account their common but differentiated responsibilities and their specific national and regional development priorities, (…) shall (…) make available to the Conference of the Parties (COP) (…) national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties" [art. 4.1. (a), UNFCCC]. In addition, each Party shall communicate to the COP a general description of steps taken or envisaged by the Party to implement the Convention [art. 12.1 (b), UNFCCC].

44. The IPCC National Greenhouse Gas Inventories Programme (IPCC-NGGIP), in close collaboration with the OECD and the IEA, develops and refines internationally-agreed methodologies for the calculation and reporting of national GHG emissions and removals and prepares and updates guidelines for national greenhouse gas inventories according to the mandate given by the COP via the Subsidiary Body for Scientific and Technological Advice (SBSTA). Every update on methodologies may then be recommended via SBSTA to COP for approval (IPCC 2003).

45. The current IPCC Guidelines group the emission sources into the following sectors: Energy, Industrial Processes, Solvent and Other Product Use, Agriculture, LULUCF and Waste. The energy section is sub-divided into "fuel combustion" and "fugitive emissions". The emissions from sources are estimated by multiplying the national or sectoral production or activity levels e.g. fuel combustion, processing, transportation, refining, or production of cement, metals and chemicals, by a fuel specific emission factor.

46. The IPCC methodology breaks the calculation of CO_2 emissions from fuel combustion into six steps:

- Step 1: Estimate apparent fuel consumption in original units;
- Step 2: Convert to a Common Energy Unit;
- Step 3: Multiply by Emission Factors to Compute the Carbon Content;
- Step 4: Compute Carbon Stored;
- Step 5: Correct for Carbon Unoxidised;
- Step 6: Convert Carbon Oxidised to CO_2 emissions.

47. In this methodology, the carbon stored is the carbon content of the fuel used for non-energy purposes that is not released, either because it is domestic production for bitumen and lubricants, or natural gas, LPG, Ethane, Naphta and Gas/Diesel oil used as a feedstock for non-energy purposes, or coking coal converted to oils and tars. There is, for instance, a default assumption that 6 per cent of the carbon in coking coal is converted to oils and tars[12]. There is no provision in the current IPCC methodology that would allow taking into account CO_2 capture and storage per se in the same way.

[12] This default assumption may lead to significant errors in certain circumstances. For more information, see the website of the International Network "Non Energy Use and CO_2 emissions" at http://www.chem.uu.nl/nws/www/nenergy/ .

48. However, during Step 1 of this methodology, i.e. estimating apparent fuel consumption, the IPCC guidelines specify that the figure for production of natural gas does not include quantities of gas vented, flared or re-injected into the well. Venting and flaring are accounted for under another category than fuel combustion: "fugitive emissions from venting and flaring". This, of course, does not address accounting for storage of CO_2 after capture has occurred.

49. In order to properly account for CCS activities under the UNFCCC, issues discussed below would need further guidance.

50. Should CCS be a source reduction or sink enhancement? The UNFCCC does not offer guidance to decide whether CCS is an emission reducing or removal enhancing activity.

51. One possibility might be that CCS be accountable as a *removal* activity, as the storage part is similar to biological sequestration in that they both take the CO_2 molecule and 'do something with it', i.e. after the emission has occurred. If this approach is chosen, the CO_2, even though not occurring physically at the source, would have to be accounted for as if emitted in order to avoid double counting. The advantage of this method would be transparency of accounting – but it would likely require a revision of the agreed methodologies for inventories. (On the other hand, in the case of CO_2 emissions captured from biomass combustion – instead of fossil fuels – it might not be appropriate to consider the captured CO_2 as "emitted", given that the IPCC Guidelines consider CO_2 emissions from biomass as giving no net contribution to the atmosphere's CO_2 level.)

52. Another possibility would be to consider CCS as a *source reduction*, that is, to only account for real emissions at plant, transport and storage levels. This could be done as an adjustment to the emission factor, as Parties to the Convention may use specific rather than default emission factors, provided they document them. This may, however, be less transparent as it would be based on a mixture of theory, experiments and end-use statistics considerations. In particular, this adjusted emission factor would have to take into account the imperfect capture process (i.e. today's capture technologies have an 85-99 per cent CO_2 capture efficiency) and thus the likelihood of resulting fugitive emissions.

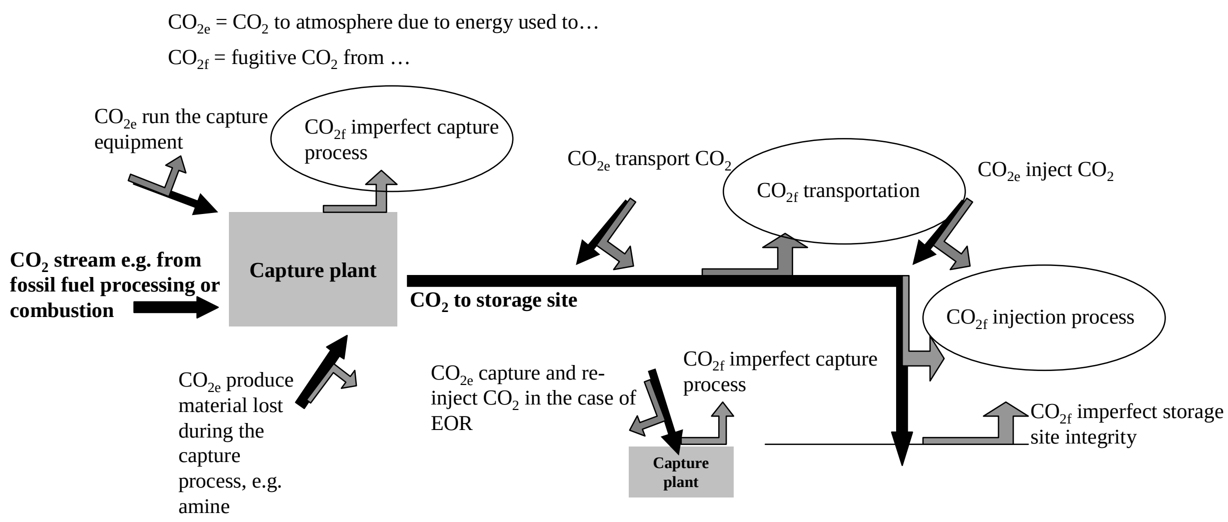
53. Again, the case of CO_2 from biomass combustion would likely require a different treatment. In such cases, only the captured CO_2 would be of interest – and not the CO_2 emitted as in the case of fossil fuel combustion – given that they would result in "negative emissions"[13].

54. Completeness is an important criterion for further guidance development. Complete accounting of emissions is one of the main principles on which every GHG accounting framework is built upon. One possibility might be to not report the CO_2-containing stream, e.g., as if it had never occurred. With current accounting rules, the CO_2 emissions due to the energy used to operate the CCS equipment would need to be reported under various inventory categories. This approach would require that fugitive emissions associated with CO_2 losses during transport and processing be somehow taken into account (see Figure 4, where these emissions are encircled). In addition, in the

[13] Opportunities for cost-effective CO_2 capture from biomass conversion exist in some countries (Morgenstern, personal communication, 2004). Ensuring a level playing field between bioenergy with CO_2 capture projects and CO_2 capture from fossil fuels, would require clarifying various concepts and issues specific to bioenergy with capture projects and reflect these in reporting guidelines. This would merit further consideration.

context of project-based mechanisms, the extra energy – and its associated GHG emissions – used in the capture and compression phases would need to be estimated and accounted for.

Figure 4: Fugitive Emissions associated with Transport and Processing during CCS



55. These fugitive emissions could be addressed by:

- either multiplying the amount of fuel processed by emission factors to take into account the various fugitive emissions such as that for stored and oxidized carbon – as in the case of emissions from fuel combustion;

- deducting the actually injected CO_2 measured at the injection point in a separate step and under a newly created category in the national GHG inventory.

56. Both approaches would be more transparent than not reporting the captured CO_2 stream at all. The second approach is more accurate if reliable data is available but it requires the measurement or calculation of injected CO_2, which, however, should not pose great additional costs. In cases where this would not be done anyway, the second approach might prove to be more costly. However, the measurement of injected CO_2 would be expected to be done routinely (i.e. even without any GHG accounting and monitoring requirements) as part of standard injection operations; it would provide essential information for the engineers involved in managing the operations. Moreover, one possible disadvantage of using the first option relying on default emission factors for fugitive emissions might be the lack of incentives for high efficiency capture. In effect, a requirement to measure the real injected CO_2 would effectively be a better means of promoting higher efficiency in capture.

57. These proposed methodologies would necessitate a revision of, or an addition to, the agreed methodologies under the UNFCCC, which requires a decision by the Conference of the Parties. In addition, issues related to escaped CO_2, EOR operations, cross-border CCS projects and international storage sites would also merit consideration, as discussed below.

58. Escaped CO_2, or physical CO_2 leakage at the storage site: Monitoring small quantities of leaked CO_2 is a challenging task. If detected, leaked CO_2 from a well to surface can in most cases be fixed (IEA, 2003a). However, in cases of a more general diffusion of CO_2 to the surface, it may be difficult to correct. Leaked CO_2 would have to be reported in national inventories, possibly under the category "fugitive emissions from fuels". Specific difficulties might occur in case of cross-border operations, as will be seen below.

59. EOR operations: Currently, the Petro-Source project (Box 2) calculates the recycled CO_2 based on the incremental change of the gas-to-oil ratio (GOR) at the production well before and after tertiary field flooding i.e. CO_2 injection. However, this approach assumes that all the CO_2 breaking through is recycled and re-injected, which might not be the case due to the imperfect capture process as mentioned earlier.

60. Cross-border CCS projects: Guidelines on how to account for CO_2 transfers between countries would either need to be agreed under the UNFCCC or the Kyoto Protocol with special attention to the case where CO_2 is exchanged between an Annex I country and a non-Annex I country, and between an Annex I country party to the Kyoto Protocol and an Annex I country that has not ratified the Kyoto Protocol.

61. In the case of a transfer between two Annex I countries bound by the Kyoto Protocol, it is possible to conceive that the host country remains responsible for the long-term monitoring of the storage site. A bilateral agreement clarifying which party and under what conditions monitors and accounts for possible CO_2 leakage (with special attention to avoid double counting of the reduced emissions) would thus be a necessary complement in the national communication of the party that claims the emission reductions. This is especially important in the light of possible unforeseeable events such as earthquakes. Transactions between private entities from different countries could very well include a sharing of the credits from reduced/avoided emissions, depending on the terms of their contract.

62. Carbon dioxide captured in an Annex I country bound by the Kyoto Protocol, but then exported to a non-Annex I country, or an Annex I country not bound by the Kyoto Protocol, could be treated through a bilateral agreement including payment for the storage of emissions transferred. However, there may be risks that the exported and stored CO_2 could simply be released there instead of being stored – or stored in bad conditions with little attention paid to long-term monitoring. Such a risk might require a different approach than in the case of two Annex I Kyoto Parties. As in the existing international legislation on waste management, it may be useful to consider the possibility that the producer of CO_2 be held responsible for it even after its transfer to another country.

63. Beyond possible rogue behaviour, there might be some monitoring issues. Under the UNFCCC and subsequent decisions by the Conference of the Parties, national communications requirements differ significantly between Annex I and non-Annex I countries. Partly as a result, only a few non-Annex I countries report regularly on their national emissions – which all Annex-I countries must do – and the accounting methodologies differ widely[14]. It is suggested, therefore, that CCS activities involving CO_2 storage in a non-Annex I country be reported adequately in the national communications of the Annex I country that deducts the CO_2 from its inventory, and that the

possibility of failure of assurance of permanence and long-term monitoring by the host country is acknowledged. A new category in the national inventory on stored CO_2 could be subdivided in CO_2 imports and exports during the accounting period and new and cumulative storage on national territory[15].

64. Various GHG units for emissions emitted, reduced or sequestered through different mechanisms have been defined in the Kyoto Protocol (e.g. assigned amount units or AAU, certified emission reductions or CERs from the CDM, emission reduction units or ERUs from Joint Implementation[16]) that require more stringent reporting guidelines than is required under the UNFCCC. They have been elaborated in the Marrakech Accords (Addendum 3, Decision 20-23 COP 7), in view of their approval by the Conference of the Parties of the UNFCCC serving as the Meeting of the Parties to the Kyoto Protocol, i.e. the body governing issues relating to the Kyoto Protocol once it enters into force. Annex I countries that are not Parties to the Kyoto Protocol would not be subject to this supplementary stringency. Current legislation does not deal with cross-border CCS projects and would need further clarification. Guidance would be especially needed to deal with cross-border projects involving CO_2 capture in an Annex I countries, party to the Kyoto Protocol, and storage in countries not party to the Kyoto Protocol.

65. CO_2 transfer to international storage sites: CO_2 could be stored in geological sites abundantly available under the oceans. This also raises the issue of monitoring and accountability for any escaped CO_2. Again, it seems appropriate that the country producing the carbon dioxide be held responsible. One possible scenario is that this responsibility be transferred via a contractual agreement whereby a country might accept the responsibility to store CO_2 for the CO_2-producing country in exchange for a payment. However, such a scenario may be interpreted as being in violation of existing international legislation on waste management if the definition of waste covers CO_2 emissions. If it does not, it may be argued that this legislation has set a legal precedent which may ultimately apply to stored CO_2. This issue might warrant further examination.

III. CARBON DIOXIDE CAPTURE AND STORAGE UNDER PROJECT-BASED MECHANISMS: BASELINES AND POTENTIAL RISKS OF ESCAPED CO_2

66. Emission baselines form the basis from which reductions (or sequestration) of emissions from any project-based activity are calculated. They are thus necessary to claim emission credits for emission reducing or removal enhancing projects under various project-based schemes. The important issue is to determine which factors need to be taken into account when developing an emissions baseline – and how. In the case of projects undertaken under the Kyoto Protocol's project-based mechanisms (i.e. Joint Implementation and the Clean Development Mechanism), such guidance is important to ensure that the credits received for CCS projects result from emission reductions that are real and additional to what would have happened in the absence of the project.

---

14 See www.unfccc.int under National Communications.

15 In addition, it would be useful to develop international standards for undertaking geological storage operations.

16 In addition, the 2001 Marrakech Accords created 'removal units', or RMUs, from using biological sinks.

67. Little-to-no guidance has been provided so far regarding the modalities to calculate and account for CCS project-related CO_2 reductions under the various project-based schemes in place or in development.

68. The only explicit reference to CCS in the Kyoto Protocol states that Annex-I countries need to research, promote, develop and increasingly use CO_2 sequestration technologies [Art. 2, par a).iv, Kyoto Protocol]. The Marrakech Accords further clarify the Protocol regarding technology cooperation stating that Annex I countries should indicate how they give priority to co-operation in the development and transfer of technologies relating to fossil fuel that capture and store greenhouse gases (Paragraph 26, Decision 5/CP.7). No text referring explicitly to CCS project-based activities can be found in the CDM and JI-related decisions.

69. Both of the two international CO_2 reporting schemes that include projects i.e. the Chicago Climate Exchange and the EU Directive establishing a Greenhouse Gas Emissions Trading Scheme (to be implemented in 2005), along with its proposed Linking Directive (i.e. proposing to link the EU Emissions Trading Scheme with JI and CDM), do not explicitly address CCS in any form yet.

70. Also, entity-level accounting frameworks such as the WBCSD/WRI GHG Protocol initiative, the American Petroleum Institute's (API) Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry and the ISO 14 064 specifications only mention CCS projects, without further guidance on how to account for them correctly.

71. CCS projects involving EOR have been reported to the US DOE 1605(b) Voluntary GHG Reporting Program but none has involved capture of CO_2 from anthropogenic sources. The US DOE is working on an accounting manual (forthcoming, 2004) addressing EOR specific issues.

72. The Canadian Voluntary GHG Reduction Registry contains the above mentioned Petro Source project (see Box 2). However, neither provided specific guidance to calculate the net emissions reductions, nor accounting guidelines are provided for CCS projects.

73. Little guidance exists today on how to calculate CO_2 emissions captured through CCS project-based activities. On the other hand, many studies have been published examining the challenges associated with determining the baseline scenario in general, and proposing recommendations on how to address them. A baseline scenario, based on several factors, would typically seek to reflect what would have happened in the absence of the project activity[17]. In the case of the Kyoto Protocol's CDM, for example, a project performing better than the baseline (i.e. generating fewer emissions than the baseline) is necessary to determine that the project leads to "additional" emission reductions compared to what would occur otherwise. It is thus important to choose an appropriate baseline scenario to minimise the risks that a project receives credits for avoiding emissions that would have been avoided anyway. Equally important is to minimise the risk of a legitimate project not being awarded appropriate credits while it has truly avoided or reduced emissions.

[17] As mentioned earlier, a domestic project-based scheme could allow projects to earn emission reductions if they perform better than a baseline based on a certain technology, for example, which may or may not reflect "what would have happened otherwise".

74. Three baseline approaches have been defined in the Marrakech Accords for the Kyoto Protocol's Clean Development Mechanism. Baselines for CDM projects shall be established based on:

- Existing actual or historical emissions; or
- Emissions from a technology that represents an economically attractive course of action, taking into account barriers to investment; or
- The average emissions of similar project activities undertaken in the previous five years, in similar social, economic, environmental and technological circumstances, and whose performance is among the top 20 per cent of their category.

75. Further, the CDM Executive Board has defined several barriers that can be used to demonstrate that a project activity is "additional", e.g. investment, technological, prevailing practice, institutional, limited information (CDM Executive Board 2002, 2003a & 2003b).

76. JI projects are to be hosted in Annex I countries with overall emission commitments (unlike CDM projects which take place in non-Annex I countries without these commitments). This is typically seen as a stronger guarantee – or a lower risk – that the baseline level for JI projects would be exaggerated to inflate the amount of emission credits that could be claimed by a project. Indeed, the JI host country, with a fixed amount of allowed emissions under the Kyoto Protocol, would have an incentive to not "give away" emission credits without corresponding emission reductions. This is a key difference with the CDM, where there is no host country-level emissions cap and where both host and investors might, in theory, have an incentive to seek to exaggerate emission reductions from a CDM project-based activity. However, the CDM project-cycle, including possibilities for the general public to review all proposed project activities, requiring that the project validation be carried out by an independent designated operational entity, and then be approved (registered) by the CDM Executive Board should work to maintain the environmental integrity of certified emission reductions (CERs) from CDM project activities.

77. The Marrakech Accords distinguish two JI cases. "Track I JI" allows for the host country alone to verify a project activity's GHG reductions or sink enhancements if the Annex I country meets certain eligibility requirements, such as having a national system for the estimation of emissions as well as a national registry and having submitted annually the most recent required emissions inventory. Under "track I JI", the host Party may issue the appropriate quantity of Emission Reduction Units (ERUs) upon the project's verification. Annex I countries that do not meet these eligibility requirements can only be involved in "track II JI", whereby the verification of a project activity's emission reductions or sink enhancement shall occur through an independent entity and the issuance of ERUs will depend on the Supervisory committee's conclusions (see Decision 16/CP.7, FCCC/CP/2001/13/Add.2). The procedure for "track II JI" projects is similar to that for CDM projects.

78. Clear guidance for the development of emission baselines is useful for project developers and also facilitates the assessment of project-based emission reductions by relevant authorities. Previous OECD and IEA studies on baselines for project-based activities (e.g. Kartha et al. 2002) have made

the case that baseline standardisation[18] (e.g. standardised emission rates, parameters and/or methodologies), if done well and tailored to appropriate project types, can simultaneously promote consistency, limit opportunities for gaming (i.e. selecting advantageous baselines) and reduce transaction costs. In this context, consideration of baselines for CCS project-based activities would also be important.

Box 3: The Weyburn CO_2 Monitoring Project

Ninety-five per cent pure CO_2 is captured at the Great Plains Synfuels Plant in Beulah, US, transported through a 330 km pipeline and injected at a rate of 5 000 tons per day in a 180 km^2 oilfield in Canada. The only commercial-size coal gasification plant in the US produces 3.5 million m^3 of natural gas per day plus by-products such as phenol and anhydrous ammonia. At the plant, CO_2 is produced from a Rectisol unit in the gas cleanup train. The CO_2 project adds about $30 million of gross revenue to the gasification plant's cash flow each year. About 20 million tonnes of CO_2 will be injected and permanently stored into the reservoir over the project's life and at least 130 million additional barrels of incremental oil are expected to be recovered. While a number of commercial CO_2 EOR projects have taken place, the Weyburn project is unique because the field has an extensive historical database that is being applied to better understand the site's CO_2 storage potential and fate. The Weyburn Project will also be the largest CO_2 flood in Canada. More info at http://script3.ftech.net/~ieagreen/project_specific.php4?project_id=102

79. While CCS project-based activities are not explicitly mentioned in either the JI or CDM decisions, it is useful to consider whether the three baseline approaches and barrier tests outlined in the CDM guidance are sufficient and adequate for CCS projects and related captured CO_2 emissions. A starting point is to examine how these approaches might be applied to the three CCS activities that currently exist, i.e. the Sleipner (Box 1), the Weyburn (Box 3) and the Petro Source projects (Box 2), as examples for future CCS project-based activities:

- If the Sleipner project chose the historical approach, the baseline scenario might be based on the emissions from stripping and venting the CO_2, as was done prior to the start of injection. In the case of a natural gas field not yet exploited, it may be argued that the marginal cost of gas injection is so important that the project would not take place in the absence of the extra revenues from selling of emissions credits. Thus the baseline could be based on the emissions from other fields delivering the unmet demand. But if the field exploitation is economically viable when the CO_2 is stripped and vented, then the field itself might be considered the project baseline;

[18] This is consistent with the Marrakech Accords, whereby the CDM Executive Board is assigned to provide guidance on "the appropriate level of standardisation of methodologies to allow a reasonable estimation of what would have occurred in the absence of a project activity wherever possible and appropriate" (Appendix C of Decision 17/CP.7). In terms of baseline guidance for JI projects, the Accords stipulate that it "shall be established on a project-specific basis and/or using a multi-project emission factor" (Appendix B, Decision 16/CP.7), implying that some form of standardisation applying to different, but similar, project-based activities could be accepted.

- If the Weyburn project chose the historical baseline approach, the baseline emissions could include the emissions vented at the synfuel plant. Alternatively, a baseline developed based on the "economically attractive course of action" approach might need to consider the likelihood that no EOR would have occurred in the absence of the project for various reasons e.g. no CO_2 readily available;

- The Petro Source project is similar to the Weyburn project in that it involves CO_2 which would most probably have been stripped and then emitted. In fact, Petro Source has chosen the historical approach for the capture part and reports on the fugitive emissions from EOR as if they would not have occurred in the absence of the project. If Petro Source had considered that the CO_2 would have been purchased from natural reservoirs (instead of the natural gas treating plants), then the fugitive emissions would have occurred anyway. Under such a scenario, the project emissions would not need to be increased by these fugitive emissions which would result in the project getting more credits (as the difference between the baseline and the project emissions would be greater).

80. Unlike the three projects considered above where CO_2 is captured anyway, potential project-based activities based on the CO_2 capture from conventional power plants or other combustion installations would involve an "additional" (i.e. not business-as-usual) process, as currently there is no regulation in the world that prohibits carbon dioxide to be emitted into the atmosphere.

81. The amount of captured CO_2 would not be equal to the project's net emission reductions. The net emission reductions associated with the CO_2 capture from conventional power plants or other combustion installations – and thus the basis for the issuance of emission credits – is calculated as the difference between the captured CO_2 and the CO_2 associated with the CCS energy penalty:

Equation: *Net CO_2 reductions = Captured CO_2 – Energy penalty-related CO_2 emissions*

82. In the case of a retrofit plant with capture equipment, the baseline emissions could not simply be the plant's historical emissions (line 1 in Figure 5), as this would not take into account the reduction in output that has to be compensated elsewhere. For example, a plant of 600 MWe without CCS may now produce ("X MWh" in Figure 5) only the equivalent of a 500 MWe plant with CCS. Therefore, the relevant questions would be: how is the difference in output (i.e. Y MWh in Figure 5) compensated, and what are the associated emissions?

83. The possible increase in emissions arising from the replacement of the lost power of the plant (i.e. the energy penalty; Y MWh in figure 5) would need to be taken into account in calculating the net emission reductions of the project as shown in Figure 3 (e.g. include GHGs from fossil fuel combustion). The net emission reductions, represented by arrow "a" in Figure 5, would be the difference between these historic emissions and the sum of actual CCS project emissions (e.g. fugitive emissions from capture process) and emissions associated with replacement of the lost power on the grid – the energy penalty.

84. The GHG emissions associated with the energy-penalty resulting from the replacement of the lost power on the grid could be calculated using a grid-based CO_2e coefficient. Different methodologies could be used to calculate such a coefficient. Guidance for CDM projects is increasing

as the CDM Executive Board approves methodologies for grid-connected projects. Moreover, many studies exist which examine the development of emissions baselines for GHG mitigation projects in the electric power sector (e.g. Kartha et al., 2002, Bosi and Laurence, 2002; Ellis, 2003). The context of the baseline analyses of these studies is, however, somewhat different, as the baseline question addressed is how to determine the power that would have been supplied from the grid in the absence of a non- or low-emitting project-based activity (while the *amount* of power generated would be the same). In the CCS retrofit case, the key baseline question is how to determine the *amount* of generated power to compensate the CCS-related energy penalty and what is the associated CO_2e emissions coefficient.

85. Nevertheless, the same baseline-related assessments and options may apply. For example, the baseline options could include the marginal capacity added to the grid during a certain time period preceding the implementation of the project; or the generation-weighted average emission factor for the grid; or an average emission factor excluding the "must-run" hydro or wind facilities, the base-load versus the peak-load power plants; or the need to build a new, additional plant of a specific fuel, type or technology; or the possibility to replace the lost power by demand-side management programmes. Previous IEA/OECD work examining the development of emission baselines guidance for GHG-mitigation project-based activities in the electricity generation sector recommended using a "combined margin" baseline calculation methodology (see Box 4).

Box 4: The Combined Margin Baseline Methodology

Previous IEA/OECD work and Kartha et al. (2003) recommend a "combined margin" methodology for estimating baselines for most grid-connected projects where the counterfactual scenario is assumed to be the ongoing expansion and operation of the overall electricity grid - rather than one specific power plant investment. The recommended *combined margin* baseline calculation (resulting in an emission rate: t CO_2/GWh), is a combination of a new project's effect on: (i) the operation of current or future power plants (referred to as the "operating margin"); and (ii) on what and/or when new facilities will be built (referred to as the "build margin").

(Adapted from Bosi and Laurence 2002 and Kartha et al. 2002)

86. Another possibility to calculate net emission reductions would be to consider the emissions that would have happened from a similar plant without capture equipment, but with an output equivalent to that of a plant with capture equipment (line 2 in Figure 5). The net emission reductions are represented on Figure 5 by the arrow "b". While this reasoning may appear less straightforward than the previous one (i.e. arrow "a") in the case of a retrofit CO_2 capture project, it may be simpler to calculate.

87. This method could also be applicable in the case of a newly-built plant. Rather than assuming that the baseline emissions would have been those of a plant with the same energy consumption or the same thermal capacity, the baseline would consist of the emissions that would have occurred if one had built a similar plant with a similar electrical (or combined energy) output.

88. Both approaches assume the same fuel and technology for the baseline scenario and for the project plant (starting with either line 1 or 2 in Figure 5) which may be questionable in some cases. For instance, it may be that an IGCC coal plant is built with capture and storage (in which case the additional cost of capture is relatively small), but if CCS had not have been considered, another type of a more ordinary coal plant may have been chosen for economical reasons. Depending on relative fuel costs and availability, a combined cycle gas turbine may even have been chosen, for example.

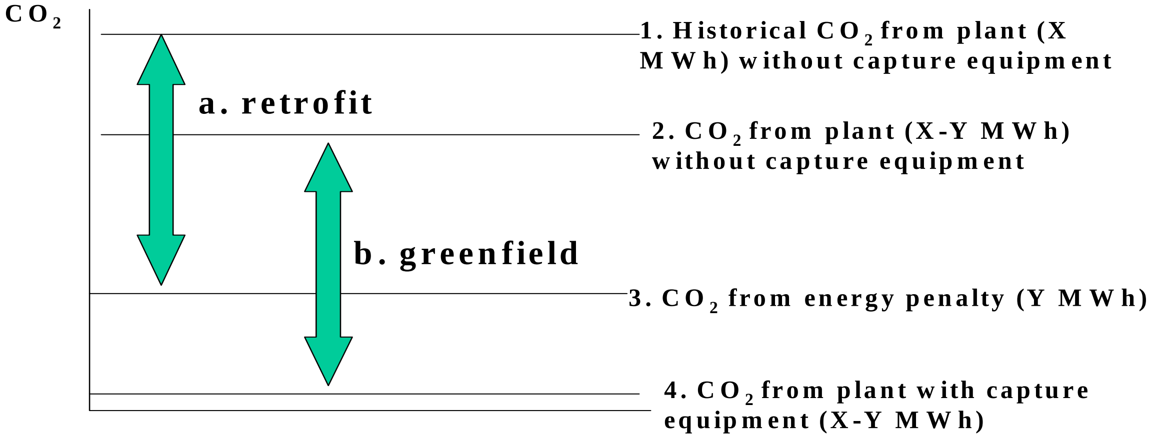
89. The two options for establishing the baseline in this case – considering the emissions "from a technology that represents an economically attractive course of action, taking into account barriers to investment", or of considering the "average emissions of similar project activities undertaken in the previous five years, in similar social, economic, environmental and technological circumstances, and whose performance is among the top 20 per cent of their category" – could be used to sort out the different possibilities in selecting the most appropriate CO_2 emission factor from the grid. However, what would be considered as "technology that represents an economically attractive course of action" or "similar project activities" in both cases would not be the CCS technology or activity, but rather the technology or activity providing the same energy output; the CCS-component would consist of the JI or CDM project-based activity.

90. In light of the recent experiences with widely differing baseline methodologies submitted to the CDM Executive Board, guidance being developed on baseline methodologies for grid-connected electricity generation projects will be useful to clarify which methodology(ies) would be most appropriate.

91. The risk of potential escaped CO_2 from storage sites might call for specific solutions in case of project-based mechanisms, especially if the "host" country is either a non-Annex I country, an Annex I country not bound by the Kyoto Protocol, or an Annex-I country not eligible for emissions trading or track I JI due to the poor quality of its inventory.

92. Captured CO_2 can both change ownership and cross boundaries. Consequently, complete accounting of all CO_2 emissions occurring during CCS activities can raise additional problems of data availability and confidentiality which need to be dealt with, bearing in mind the trade-off between accuracy and reasonable costs of accounting.

Figure 5: Two Baseline Possibilities for Calculating Net Emission Reductions by CCS



93. Beyond monitoring issues, several scientific research efforts concentrate on the development of discount factors for various levels of site integrity, assuming that minimal fractions of the emissions might be reemitted at some time (Bachu, 2003). Such discount factors could be integrated in the calculation of the credits generated by CCS projects – that is, the amount of tonnes credited in one year will be less than the amount stored in the same year[19]. However, the choice of the appropriate discount factor is a rather complex issue, linked to the assumed value of temporary storage instead[20] rather long-term storage.

94. A frequent assumption is that "leakage from storage facilities would weaken CCS as a source of permanent emission reductions", though CCS could still provide valuable temporary storage while less costly permanent means of mitigation are being developed (e.g. renewable energy sources) (Anderson & Newell, 2003). Herzog et al. (2003) have considered in more depth the value of temporary or "transitional" storage[21] that would likely be offered by ocean injection (or even geological sequestration in some cases, such as using some depleted oil and gas fields). They show that by comparison with permanent storage, the transitional storage value depends on some critical assumptions on how the carbon price evolves in the future. If it is constant, transitional storage would have a value close to that of permanent storage. Any future escaped CO_2 would simply be offset by some additional reduction in emissions elsewhere, at a cost that has a low net present (discounted) value. If the carbon price grows at the same pace of discount rate, the value of transitional storage is

19 These discount factors might be simple numbers between 0 and 1. They do not need to be "exponential" discount factors resulting from the use of constant discount rates compounded over years, as in the case of economic discounting or interest rates.

20 For a debate on storage site integrity, see Bachu, S. and Celia, M., 2002.

21 The term "temporary storage" might not be appropriate when applied to geological storage, as the time-scale might still be longer than other storage options considered (e.g. forestry). Ongoing IPCC discussion on CCS refer to the term "transitional storage".

rather small. If the carbon price increases and then becomes constant because some backstop technology enters the picture, the value of transitional storage would also be close to that of permanent storage if the backstop technology entry is “not too distant in the future”.

95. The value of transitional storage must be looked at in the context of the UN Convention on Climate Change and its ultimate objective: stabilising GHG atmospheric *concentrations*. As far as CO_2 is concerned, and whatever the level of concentration eventually reached, stabilisation is likely to require large global emission reductions, of the order of -50 per cent in the coming decades, and perhaps up to -95 per cent in the following centuries. As noted by the IPCC in its Third Assessment Report, in order to maintain a constant future CO_2 concentration, anthropogenic CO_2 emissions would have to be eventually reduced to the level of persistent natural land and ocean sinks. These may not exceed 0.3 to 0.6 $GtCO_2$ per year[22], while current energy-related CO_2 emissions are almost 30 $GtCO_2$ per year.

96. This would be close to a fixed limit on global emissions. The optimal use of this limited atmospheric capacity to absorb CO_2 emissions would be driven – as Hotelling showed in 1931 with respect to limited fossil fuel supply – by a price escalating at the pace of the economic discount rate, in the absence of a new, “backstop” energy technology. This is precisely what would give little value to temporary storage – following the analysis of Herzog et al. (2003).

97. If CCS were to become one of the most important options to reduce CO_2 emissions, large quantities of CO_2 would have to be stored over this century. Dooley and Wise (2002) quote new MiniCAM modelling results that seek to estimate economically efficient ways to reach various stabilisation targets along the emission pathways suggested by Wigley et al. (1996). The model combines both capture and storage along with more extensive use of non-carbon fuels and improving end-use efficiencies. Dooley and Wise report that the cumulative amount of carbon disposed of over this century would be about 100 GtC, 200 GtC and 340 GtC to reach concentration levels of 650,550 and 450 ppm respectively. Other estimates (i.e., Hepple & Benson, 2002) that give a more prominent role to CCS technologies in achieving the same concentration levels lead to higher volumes of CO_2 stored.

98. Escaped CO_2 into the atmosphere would need to be considered and an assessment made on what would constitute an acceptable seepage rate to the atmosphere. Unfortunately, there are no reliable experimental data available to accurately estimate the rate of escaped CO_2 from storage into the atmosphere. However, modelling work has been done to test the implications of different hypothetical CO_2 seepage rates from geological storage sites into the atmosphere. Despite their divergences, the models seem to suggest that a 1 per cent seepage rate would not allow stabilisation of CO_2 concentrations; 0.1 per cent would allow stabilisation but might involve large costs as escaped emissions from storage sites would need to be offset by deeper emission reductions elsewhere; 0.01 per cent seepage rate, however, would appear compatible with stabilisation of concentration goals in all cases. While most experts seem to believe that geological storage can well provide effective retention with seepage rates below 0.01 per cent, there is for now, as mentioned above, little scientific evidence to prove or disprove this assumption. In any case, such figures might be worth keeping in

[22] Given current ocean and land uptake, a balance between emissions and uptake might be reached when emissions are reduced to approximately half of current levels. Over time however, as the long term release of

mind when selecting storage sites – as seepage rates may well be very site specific and depend on a large number of geological factors as well as history of human usages, notably in the case of depleted fossil fuel reservoirs. Many potential storage reservoirs might have hundreds of thousands of wells, providing potential leakage pathways towards the surface.

99. In sum, every effort should be made from the onset to ensure the integrity of geological storage sites, so as to provide sufficient assurance that CO_2 emissions would not escape from the storage sites, at least in the absence of unexpected extreme events. If this were possible, there would be no need to engage in the difficult discussion on the true value of avoided emissions through temporary storage, and on the life span that would need to be considered. As a result, only fugitive emissions from activities associated with capture and storage processes would have to be accounted for in establishing a CCS project's emissions. However, until there is greater certainty on the complete integrity of CO_2 storage sites (i.e. no seepage would occur), it seems necessary to develop means to assess possible risks of CO_2 leakage into the atmosphere and take them into account in the assessment of emission reductions from CCS project-based activities.

100. Finally, demonstration of "additionality" in the sense of the CDM is likely to be straightforward for most CCS projects, as they typically imply additional expenses in both capital and operations that are not compensated by revenues other than those stemming from the sale of "certified emission reductions" (for CDM projects) or other types of carbon credits. They cannot be described as business-as-usual activities. Capture and storage associated with enhanced oil recovery operations, however, may be more difficult to prove additional in the CDM framework. This could be the case if the additionality determination of such projects relies on traditional financial assessments (sometimes referred to as "investment" or "financial" additionality) – which have been used in some of the decisions on methodologies taken by the Methodology Panel (advising the CDM Executive Board) and the Executive Board of the CDM – unless barriers to such investments can be demonstrated.

IV. INSIGHTS, AND CONCLUSIONS

101. Carbon dioxide capture and storage offers important possibilities for making further use of fossil fuels more compatible with climate change mitigation policies – in particular in using coal for producing electricity or other energy vectors such as hydrogen.

102. There is dire need, however, for decisions about the methodologies to account for capture and storage in national greenhouse gas inventories for the purpose of the United Nations Framework Convention on Climate Change and related existing or forthcoming international agreements. These decisions should not be limited to how capture and storage should be accounted for when both (i.e. capture and storage) take place in a single country, but should also consider the possibility of cross-border projects in countries with different obligations regarding both the Convention and the Kyoto Protocol or other climate change agreements.

103. Developing appropriate methodological guidance for establishing baselines for such activities in the framework of project-based mechanisms could greatly help the dissemination of these technologies. It might be particularly useful to disseminate CCS technologies to developing countries.

CO_2 from the ocean into the atmosphere continues, the stabilisation of atmospheric concentrations would require greater reductions.

The two largest developing countries, China and India, have important cheap coal resources and growing electricity needs. Helping such countries to adopt the most efficient plant designs is likely to provide large short-term cost-effective emission mitigation potential. However, in the longer term, helping them and creating incentives, through project-based or other mechanisms, to implement CCS technologies would be important for global GHG mitigation.

104. This paper suggests that the most important baseline question to be dealt with is that of the energy penalty associated with CCS processes, and outlines various possibilities of handling this. It suggests that fugitive emissions from transportation and processing activities could be monitored or at least estimated and accounted for in the emissions of the project – so they would be deducted from the computed credits attributed to CCS projects. The GHG emissions associated with the energy penalty resulting from the replacement of lost power on the grid could then be calculated using a grid-based CO_2e coefficient – for which methodologies have already been developed. It acknowledges current data gaps in calculating seepage rates from storage sites, but suggests that assessing and determining acceptable seepage rates from the geological storage will be critical for the viability of the technology as a long-term GHG mitigation option.

105. Ensuring near-elimination of seepage and proving that any seepage occurs at a rate below 0.01 per cent – as many experts currently believe – should be an important objective for CCS-related research. Until then, recognising and addressing the potential risk is likely a necessary part of the assessment of the mitigation effect of CCS activities in the short-medium term.

ACRONYMS

CCS	Carbon capture and storage
CDM	Clean Development Mechanism
CO2	Carbon dioxide
ECBM	Enhanced coal bed methane
EOR	Enhanced oil recovery
GHG	Greenhouse gases
GtC	Giga (10^9) tonnes of carbon
$GtCO_2$	Giga tonnes of carbon dioxide
GWh	Gigawatt hour
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
NO_X	Nitrogen oxide
OECD	Organisation for Economic Co-operation and Development
OSPAR	Convention for the Prevention of the Marine Environment of the North-East Atlantic
SBSTA	Subsidiary Body for Scientific and Technological Advice
SO_2	Sulphur dioxide
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	United States Department of Energy
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute

REFERENCES

Anderson, S & R. Newell, 2003, *Prospects for Carbon Capture and Storage Technologies*, Discussion paper 02-68, Resources for the Future, Washington D.C., January.

Bachu, S., 2003, Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media, *Environmental Geology*, v. 44, no. 3, p. 277-289.

Bachu, S. and Celia, M., 2002, *Geological sequestration of CO_2: is leakage unavoidable and acceptable?*, Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, October.

Bosi, M., 2001, *An Initial View on Methodologies for Emission Baselines: Electricity Generation Case Study*, OECD and IEA Information Paper, Paris at http://www.iea.org.

Bosi, M. and A. Laurence, 2002, *Road-Testing Baselines for Greenhouse Gas Mitigation Projects in the Electricity Power Sector*, OECD and IEA Information Paper, COM/ENV/EPOC/IEA/SLT(2002)6 at http://www.iea.org.

CDM Executive Board, 2002, *Project Design Document*, at http://cdm.unfccc.int/Reference/Documents/cdmpdd/English/cdmpdd.doc

CDM Executive Board, 2003a, Attachment A to Appendix B, report to 7th meeting of EB, SSPanel (on barriers to project implementation).

CDM Executive Board, 2003b, *Further clarifications on methodological issues*, Annex-I 10th of meeting report, at http://cdm.unfccc.int/EB/Meetings/010/eb10repan1.pdf.

Davison, J., 2002, *Costs of renewable energy and CO_2 capture and storage*, Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, October.

Dooley, J.J. & M.A. Wise, 2002, *Why injecting CO_2 into various geological formation is not the same as climate change mitigation: the issue of leakage*, Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, October.

DTI, 2002, *Carbon Dioxide Capture and Storage*, report of the International Technology Service Mission to the USA and Canada.

Ellis, J., 2003, *Evaluating Experience with Electricity-Generating GHG Mitigation Projects*, OECD and IEA Information Paper, OECD/IEA at http://www.oecd.org/env/cc/.

Gielen, D., 2003a, *Uncertainties in relation to CO_2 capture and sequestration – Preliminary results*, Paris.

Gielen D., 2003b, *The Future Role of CO_2 Capture and Storage Results of the IEA-ETP Model*, Paris.

Hepple & Benson, 2002, *Implications of Surface Seepage on the Effectiveness of Geological Storage of Carbon Dioxide and a Climate Change Mitigation Strategy*, Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, October.

Herzog, H., 2000, The economics of CO_2 separation and capture, *Technology*, vol. 7, supplement 1, pp. 13-23.

Herzog, H., K. Caldeira & J. Reilly, 2003, An issue of permanence: Assessing the effectiveness of temporary carbon storage, *Climatic Change*, forthcoming.

Hotelling, H., 1931, The Economics of Exhaustible Resources, *Journal of Political Economy*, 39, 137-75

IEA, 2002a, *World Energy Outlook*, OECD/IEA, Paris.

IEA, 2002b, *Beyond Kyoto – Energy Dynamics and Climate Stabilisation*, OECD/IEA, Paris.

IEA, 2003a, *Policy Issues Linked to Carbon Sequestration*, IEA/SLT(2003)26.

IEA, 2003b, *CO_2 Emissions from Fuel Combustion: 1971-2001*, IEA/OECD, Paris.

IEA Greenhouse Gas R&D programme, 2003, *Greenhouse gas emissions from power stations*, webdocument, at http://www.ieagreen.org.uk/emis4.htm

IPCC, 1996, *Guidelines for National GHG Inventories*, at http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

IPCC, 2000, *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, at http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm.

IPCC, 2001, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, N.Y., USA, 881 pp.

IPCC, 2002, *Workshop on CO_2 Capture and Storage*, *Proceedings*, Regina, Canada, at http://www.climatepolicy.info/ipcc/index.html.

IPCC, 2003, *National Greenhouse Gas Inventories Programme*, at http://www.ipcc-nggip.iges.or.jp/.

Kartha, S., M. Lazarus, and M. Bosi, 2004, Baseline recommendations for greenhouse gas mitigation projects in the electric power sector, *Energy Policy*, vol. 32 pp. 545-566

McKee, B. 2002, *Solutions for the 21st Century, Zero Emissions Technologies for Fossil Fuel*, International Energy Agency Working Party on Fossil Fuels, OECD/IEA, Paris.

Möllersten, K., J. Yan, and JR Moreira, 2003, Potential market niches for biomass energy with CO_2 capture and storage – Opportunities for energy supply with negative CO_2 emissions. *Biomass and Bioenergy* 25(3): 273-285

Obersteiner, M., Ch. Azar, P. Kauppi, K. Möllersten, J. Moreira, S. Nilsson, P. Read, K. Riahi, B. Schlamadinger, Y. Yamagata, J. Yan, J-P van Ypersele, 2001, Managing Climate Risk, *Science* 294 (5543): 786-787.

OECD/IEA, 2000, *Estimating the Unknown*, at http://www.iea.org/dbtw-wpd/bookshop/add.aspx?id=73

Statoil, *Sleipner project in Norway*, at http://www.statoil.com/statoilcom/svg00990.nsf/web/sleipneren?opendocument.

Thambimuthu, K., 2002, *Zeroing emissions with CO_2 capture and storage*, presentation at COP8, on http://www.iea.org/envissu/cop8/ieaside/kelly.pdf.

Wigley, T.M.L., R.G. Richels and J.A. Edmonds, 1996, Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations, *Nature*, 379 (6562): 240-243, January 18.